Technology Demonstration Mission
Solar Electric Propulsion
Annual Review – March 2, 2023

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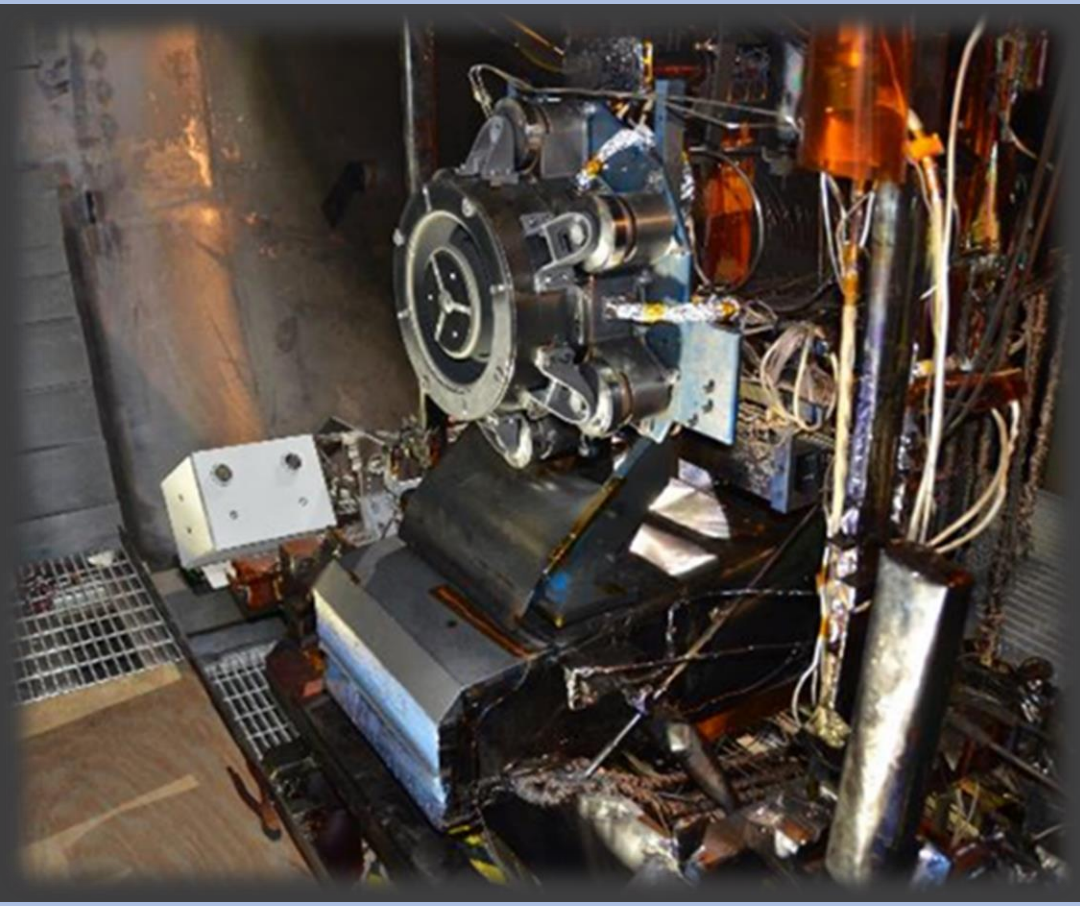
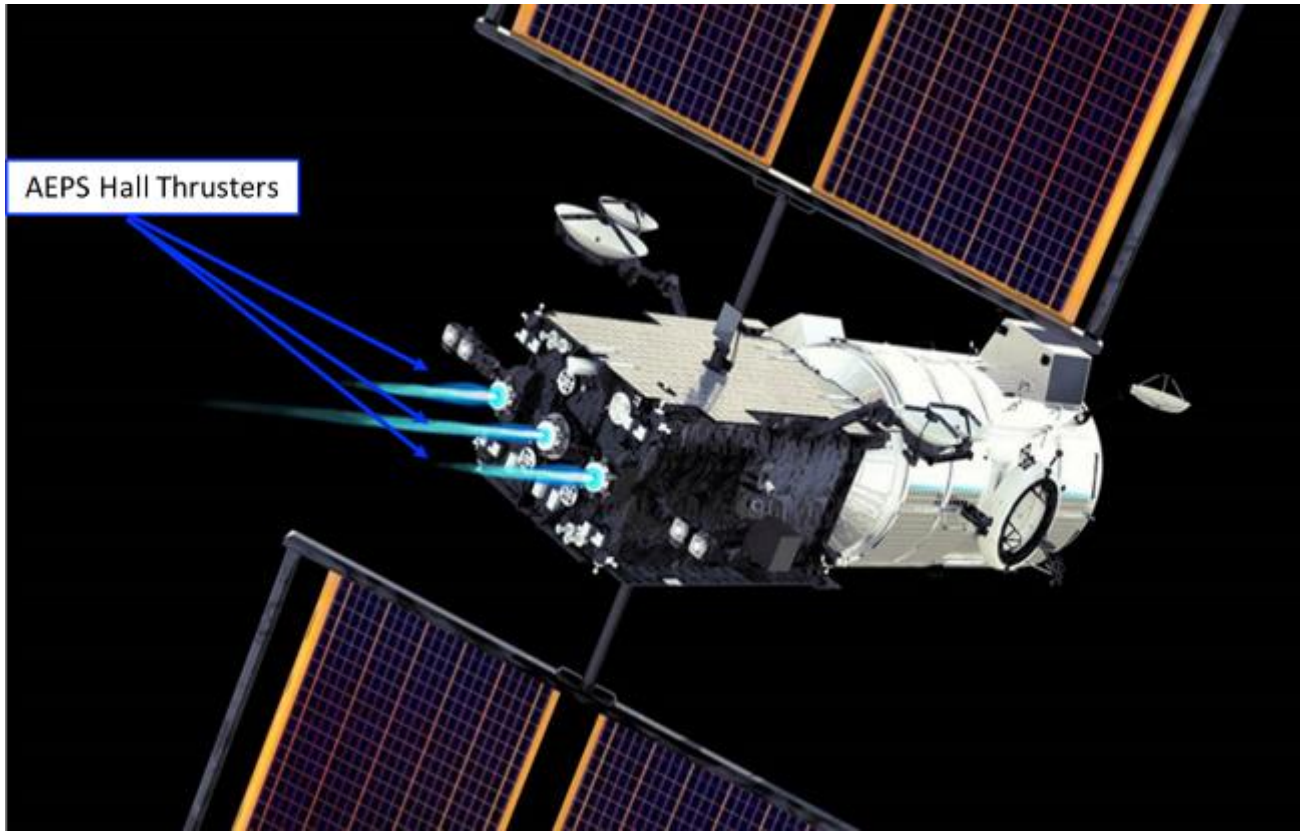
NASA Glenn Research Center
March 2nd, 2023

NASA Technology Demonstration Missions (TDM)



Solar Electric Propulsion Project Overview



Project Description	Key Information	Elements
The Solar Electric Propulsion (SEP) project is developing and qualifying an advanced 12 kW Electric Propulsion (EP) thruster to the Power and Propulsion Element (PPE) requirements, which are applicable to human/robotic exploration and commercial spaceflight missions.	Project Phase: C Milestone Dates: QSAR#1: Q1 FY2025 QSAR#2: Q2 FY2026 QM2 Wear Test: Q4 FY2028	12 kW magnetically shielded Hall-effect EP Thruster ** The SEP Project includes Qualification of Hardware; The PPE flight hardware is separate **

Cancellation of the Plasma Diagnostic Package

STMD AA led DPMC on 27-Apr-22 and decided to initiate an orderly shutdown of the PDP subproject

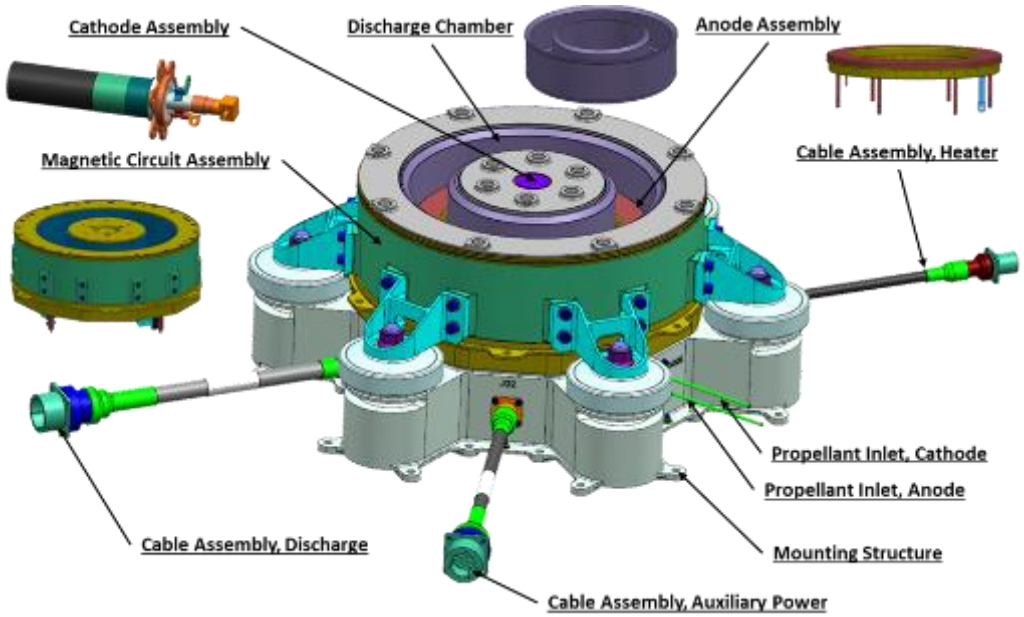
- **A revised estimate to complete increased PDP sub-project costs by $2.7M which triggered the need for a Continuation Review**
- **PDP hosted a Continuation Review on 8-Apr-22**
  - Strong technical consensus for continuing
  - Power & Propulsion Element (PPE) felt mass savings on spacecraft was higher priority (all non-critical options being targeted)
  - Strong support from other stakeholders
- **PPE mass concern and Advanced Electric Propulsion System (AEPS) poor contract performance following CDR necessitated the cancellation**

- **SEP Plasma Diagnostics Objective**
  - SEP shall provide GFE plasma diagnostics to characterize high power SEP performance and space vehicle interactions on USA space flight missions including the Power & Propulsion Element (PPE)
- **Access to Space/Demo Details**
  - Class D hardware was to be delivered as Government Furnished Equipment (GFE) to PPE by May 2023

SEP Project

The SEP Project includes the following activities

- **Develop, manufacture, and qualify high-power (12 kW) next generation electric propulsion thruster for space flight system integration**
- **Mature manufacturing processes** to enable a commercially available high-power (12 kW) electric propulsion thruster for space vehicle integration
- **Complete qualification of 12 kW Advanced Electric Propulsion System (AEPS) thruster** to include qualification wear-testing to at least 100% of the PPE mission-based, per-thruster Xenon throughput requirement (expected to be 23,000 hrs)
- **Reduce interface and plasma interaction uncertainty** to improve probability of demonstration mission success, enable private-sector infusion, and enhance future exploration application of the SEP technologies
- **Publish and distribute** electric propulsion thruster life qualification, plasma plume model predictions, and interface information to allow for US private sector assessment, understanding, and infusion of the electric propulsion system
- **Develop the interface between the mission user (PPE) and electric propulsion contractor (Aerojet Rocketdyne)** to ensure electric propulsion requirements, capabilities, and qualification meet the mission needs



SEP Governance

- **Power & Propulsion Element (PPE) and the Exploration Systems Development Mission Directorate (ESDMD) have defined roles in the governance of SEP**
  - Space Technology Mission Directorate (STMD)/Technology Demonstrations Missions (TDM) manages and provides governance of the SEP Technology Objectives and development and qualification of the AEPS Thruster
  - ESDMD/PPE is responsible for the identification and control of the NASA AEPS Thruster requirements and risk management
  - TDM and PPE maintain control boards required for making changes to the objectives and requirements within the SEP Project
  - SEP project is responsible for implementation of the NASA AEPS Thruster requirements and contractor oversight
  - PPE provides the technical requirements for the AEPS contract
    - Changes to the requirements documentation needs approval from PPE
    - For PPE driven requirement changes to the AEPS contract, PPE is responsible for the associated development and qualification cost
  - SEP and PPE hold joint Review Boards and Control Boards for changes or items that could have technical, cost or schedule impacts to PPE
    - The joint boards to reduce time and increase integrated review efficiency
    - The joint boards are jointly chaired by the TAs for Engineering and SMA and SEP and PPE Project Managers

Advanced Electric Propulsion System (AEPS) Contract Status

- **AEPS Contract**
  - Cost Plus Fixed Fee contract plus Performance Incentive Fee (schedule & technical)
  - Solicitation Released in July 2015, Awarded to Aerojet Rocketdyne (AR) in May 2016
  - Original Contract for AEPS String Development with Option to deliver qualification and flight strings
- April 2020, SEP engaged in re-baseline efforts to align with PPE thruster-only GFE requirements
- **March 2021: ECP-05 Awarded for two (2) qualification thrusters only**
- July 2021: KDP-C replan memorandum signed
- **December 2021: ECP-06 awarded for fabrication of three (3) flight thrusters with ESDMD funding**
- **September 2022: ECP-07 awarded for updated requirements from PPE**
- **February 2023: ECP-08 awarded for the descope of the DCSU**

CLIN	Scope of Effort under CLIN	Status
CLIN 1	Development w/ Hardware for EP String (HCT, PPU & XFC)	Close-out in Oct 2020
CLIN 2	Long Lead Material Items for Qual & Flight	PoP ends in 3QFY23
CLIN 3	Option – Qualification and Space Flight hardware delivery	Removed
CLIN 4	Capital Assets (no assets identified)	N/A – not proposed
CLIN 5	Performance Incentive Fees	Not earned; Removed
CLIN 6	Qualification effort of EP String	PPU/XFC descoped in Jan 2021, Thruster activities transferred to CLIN 7 in ECP-05
CLIN 7	Thruster-only development and qualification effort	ECP-05 Awarded in March 2021
CLIN 8	Thruster-only flight hardware delivery & acceptance testing	ECP-06 RFP released May 2021, awarded Dec 2022
CLIN 9	Flight Long Lead Material Initial Fabrication activities	Unsolicited Proposal to begin early Fab work (Jul 2021)

Advanced Electric Propulsion System (AEPS) CDR Overview

- **Aerojet Rocketdyne (AR) led CDR held on March 8-10, 2022**
  - Summary from the SEP Standing Review Board (SRB) Assessment
    - The SRB found that the project met 21 of the 23 applicable success criteria defined in NPR 7120.5E, NPR 7123.1B, and the SEP-EP Thruster Terms of Reference (ToR)
    - Most concerns identified were around schedule, project reserves, risk management and systems integration
      - Seven (7) Requests for Action (RFA) and seven (7) Advisories were generated and shared with the project
      - Two RFAs focused on integration with PPE while others focused on schedule margin, project cost, project risk, thermal environment, and finalizing documentation
    - Selected project strengths per the SRB
      - Significant progress has been made since the Preliminary Design Review
      - The design presented is the culmination of ~10 years of development work including three NASA built Test Development Units (TDUs) and two AR built Engineering Test Units (ETUs), providing significant risk mitigation
      - The thruster component design is mature with adequate technical margins
  - 34 of 35 thruster RFAs from AR and SEP have been closed, including 11 of 12 NASA RFAs
  - **SRB Final Report (April 2022): "The SEP project successfully demonstrated that the technical maturity of the thruster design is appropriate and none of the SRB findings presented a lien on proceeding with qualification testing and flight fabrication.**"

Qualification Module-1 Production

Anode Assembly (29-Mar-22) Complete

Magnetic Circuit Assembly (14-Jul-22) Complete

Harness Fabrication (13-Jan-23) Complete

Green – Complete
Blue – In work
Red – Delayed

Thruster sub-assembly (23-Jan-23)

- Anode isolator (complete)
- Mounting structure (complete)
- Magnetic circuit (complete)
- Anode (complete)
- Discharge chamber (complete)

Harnesses Integration (3-Mar-23)

Thruster Assembly Complete (07-Apr-23)

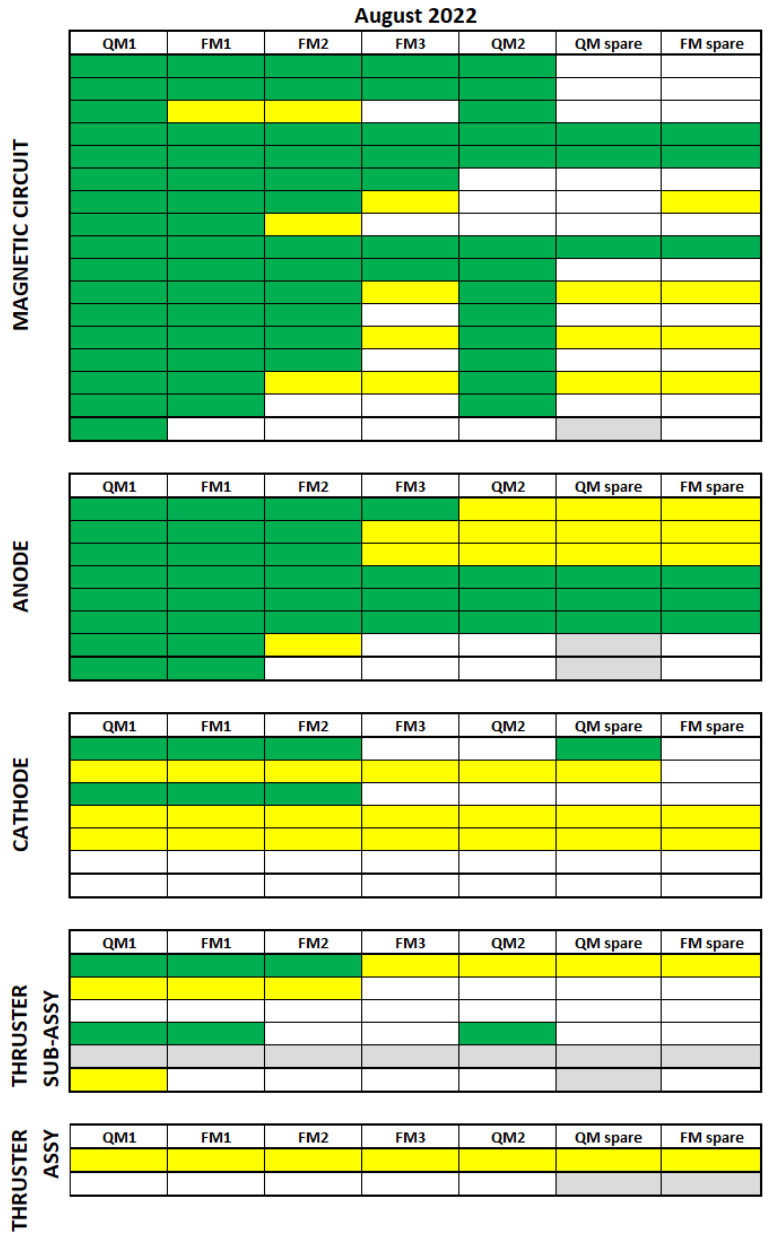
Cathode sub-assembly (24-Feb-23)

- Cathode Tube (complete)
- Heater Braze Assy (complete)
- Terminal Support Housing (complete)
- Insulator Body (complete)
- Keeper (complete)

Integration of Cathode and Thruster sub-assemblies (16-Mar-23)

AEPS Production

- **Since CDR, AR has continued to make strong progress on the production of qualification and flight thrusters**
  - Qualification Module (QM)-1 fabrication is nearly complete
  - QM-1 and Flight Module (FM)-1 cathodes nearly complete
  - FM-1 magnetic circuit and anode assemblies complete, at thruster sub-assembly level
  - FM-2 magnetic circuit and anode assemblies complete, at thruster sub-assembly level
  - FM-3 magnetic circuit and anode assemblies in work
  - QM-2 magnetic circuit and anode assemblies in work



AEPS QM-1, FM-1, FM-2, and FM-3 Thrusters in Assembly

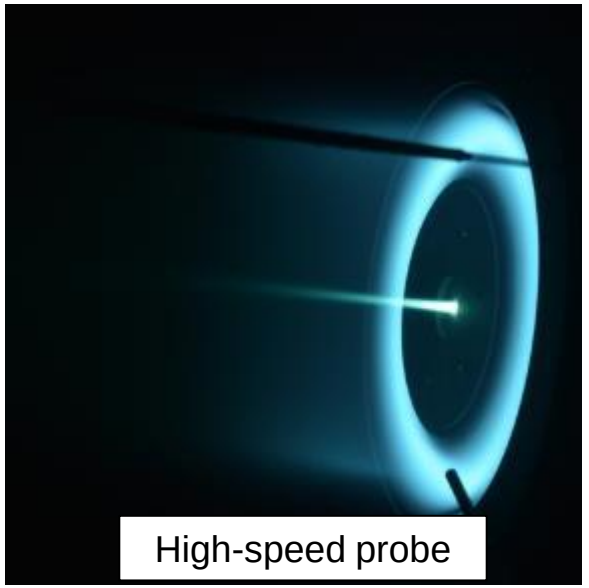
Technology Development Advancements

SEP-PPE Integration

- **NASA SEP & PPE teams have been working to coordinate the integration of the AEPS thruster onto the PPE spacecraft**
  - Joint ICD content finalized by NASA, AR, and Maxar, with informal review by all parties
  - NASA completed formal review of the Joint ICD in January 2023
- **Biweekly 3-way (NASA, AR, and Maxar) technical integration meetings**
  - Identify key issues for integration
    - PPE harness update is being worked through this forum and harness specific tiger team
  - Path for identifying development issues
- **12 kW Maxar Power Processing Unit (PPU) & Xenon Flow Controller (XFC) integration testing with AEPS ETU-2 thruster planned for summer 2023**
  - Second phase of integrated testing
  - XFC updated for AEPS flow requirements
  - Test planned to be performed with post-CDR PPU and Thruster Auxiliary Support Unit (TASU)

JPL Risk Reduction Testing

- **Risk Reduction testing being performed at JPL on TDU-2, aimed at validating key physical mechanisms contributing to pole cover erosion in Hall2De simulations**
- **High-Speed Probe Risk Reduction Test**
  - Using high-speed probes to measure transient and time-averaged plasma properties in the near plume and discharge channel
- **Laser-Induced Fluorescence (LIF) Risk Reduction Test**
  - Measuring time-averaged azimuthal ion velocity distributions
  - Main beam, side plume, near pole, and cathode plume scans
  - Demonstrated that waves excited in the cathode plume by applying an RF voltage on the cathode keeper can be detected with LIF
- **The data obtained to-date are consistent with the wear model being used (in part) to verify thruster lifetime, which increases the confidence in the model**
  - Provides extrapolation of ground test to in-space operation and verification of 1.5x margin to lifetime that will be demonstrated by QM-2 life test


High-speed probe


LIF setup

Component Qualification Testing

Component qualification testing has been initiated

- **Inner and outer magnet coils**
  - Life cycle testing was initiated on 2-Dec-22 at JPL
  - 2550 cycles (1.5x cyclic requirement) planned, with expected completion date in September 2025
  - Current cycle count is ~170-200 cycles

- **Thermal components (magnet survival heaters and temperature sensors)**
  - Thermal components installed in JPL test facility
  - First thermal cycle was completed on 15-Feb-23

Six coil fixtures installed at the CTF

Thermal component fixtures installed at the CTF

Other Technical Accomplishments

- **Initiation of requirements verification**
  - NASA has reviewed 8 Verification Closure Notices (VCNs) to-date, with 5 AR requirements and 3 NASA parent requirements verified

- **Significant progress made in qualification and flight test preparations, including compliance to NASA-STD-5005D of both AR- and NASA-provided Ground Support Equipment (GSE)**
  - NASA-STD-5005D compliance assessments have been completed and approved for NASA-provided GSE needed to perform qualification and flight thruster acceptance testing at GRC
  - 28 of 36 compliance assessments for AR-provided GSE have been reviewed and accepted by NASA
    - Formal approval of all compliance assessments expected to occur by March 2023

Technical Issues and Risks

Issues

- **Cathode low cycle fatigue (LCF) on cathode heater termination joint**
  - Open issue from CDR – AR cannot verify ability of joint to meet cyclic requirements via analysis
  - Closed by AR after additional modeling and risk reduction testing on EDU-1 development cathode
  - NASA assessing options to reduce risk inherent with AR's approach with respect to variation in materials properties of test samples
    - Proposed NASA independent design assessment activity will be taken to ERB/PCB for project approval

Risks

- **Top risk is the "Impact of High-Voltage Transients on AEPS Thruster" (EP-162)**
  - Actively mitigating with ongoing SEP testing on development thrusters in VF-6 to better characterize magnitudes of transients
  - Will share data acquired with PPE to better define transients at interface and any associated risks to spacecraft

Programmatic Issues and Risks

Issues

- **Non-Conformances (NCs) related to first time hardware build and assembly**
  - Large number of NCs on the first build of the thruster has caused negative cost and schedule variances
  - Lessons learned from the NCs has improved the build and assembly of the flight thrusters
- **Consistent cost overruns during production**
  - CPI cumulative is 0.85 since CDR
  - Program Office planning has ensured project budgeted reserves protect against this cost threat

Risks

- **Requirements changes driven by PPE updates**
  - New or updated requirements threaten the thruster delivery dates because the project is deeply into production
    - Project continues to be involved in the PPE harness updates and monitor possible technical and schedule impact
- **Thruster life qualification from 1x to 1.5x by analysis requires a validated numerical model**
  - Project continues to apply resources to mitigate the risk such as testing to improve model

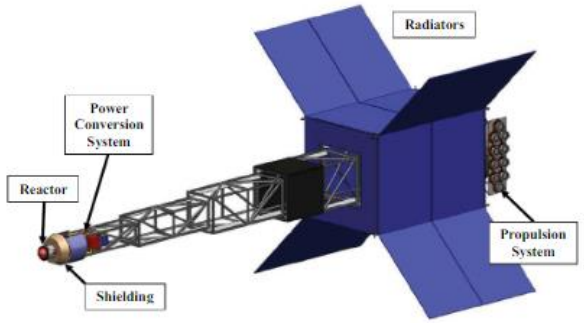
AEPS Infusion

While Gateway/PPE is the first and requirement-defining user for the AEPS thruster, NASA and Aerojet are actively seeking additional users and identifying future mission applications

- **Aerojet-Rocketdyne is actively promoting AEPS for commercial use**
  - "AEPS will significantly advance the nation's commercial space capabilities" (https://www.rocket.com/space/space-power-propulsion/solar-electric-propulsion)
  - AR continues to invest internal resources to develop a commercial package, confident of commercial and other-government users

- **NASA and AR are collaborating to promote AEPS for future NASA missions**
  - SEP and AR both promoted AEPS at the January SMD 2023 Technology Showcase for Future NASA Planetary Science Missions
    - Productive conversations with New Frontiers mission planners
    - Follow-up conversations have occurred with multiple NASA mission centers
  - AEPS thrusters were provided to SMD as part of a short list of candidate technologies for incentivization in the New Frontiers-5 Announcement of Opportunity

- **AEPS was called out as 1 of 2 viable technologies for a potential Nuclear Electric Propulsion Demonstration Mission (NASA's 2022 Prometheus and Constellation Workshop)**
  - 10 kW NEP could enable a class of outer solar system missions not otherwise possible and could significantly enhance a range of other deep-space mission concepts; John Casani, 2020, http://hdl.handle.net/2014/47277



300 kW NEP demonstrator
Bragg-Sitton, 2011

AEPS 1-Year Look Ahead

- Qualification Module (QM)-1 Final Assembly Complete – April 2023
- QM-1 Qualification Testing starts at NASA GRC – May 2023
- Key Decision Point-D – May 2023
- Flight Module (FM)-1 Deliver to NASA – January 2024
- FM-2 Deliver to NASA – April 2024
- QM-2 Final Assembly Complete – June 2024
- FM-3 Deliver to NASA – July 2024

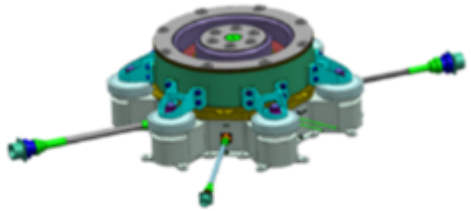
Summary

- **SEP is confident the AEPS thrusters will meet PPE mission needs**
  - Engineering hardware exceeds minimum PPE requirements (performance, life, thermal and structural margins)
- **Component qualification testing has begun at JPL**
- **Thruster production is proceeding well with no change in the delivery dates since the award of ECP-07**
- **Aerojet Rocketdyne leadership continues strong working relationship**
  - Project has healthy schedule margin, but cost variances are still a concern
  - Cost and schedule earned value metrics have stabilized in the last several months
- **Qualification testing of the first thruster will begin in May 2023**

BACKUP CHARTS

Solar Electric Propulsion Overview

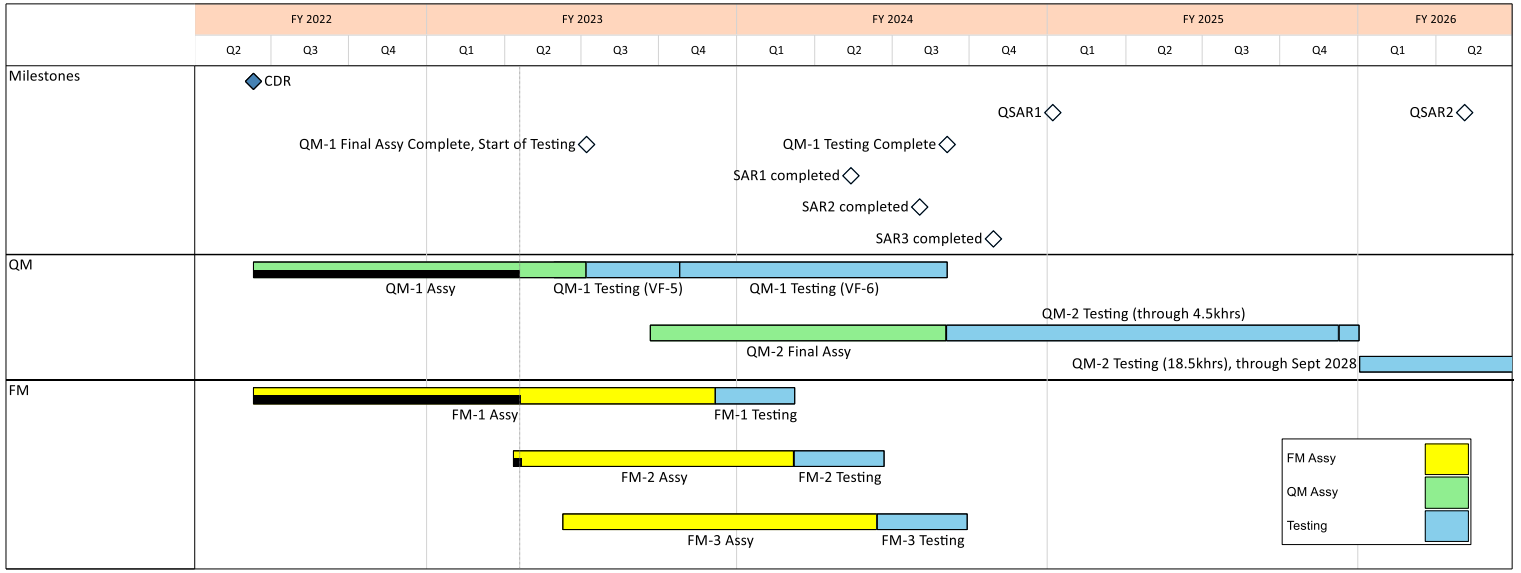
Solar Electric Propulsion (SEP)



Develop and qualify an advanced 12 kW class EP thruster applicable to exploration & commercial spaceflight: Mature manufacturing processes to enable a commercially available high-power next generation electric propulsion thruster for space vehicle integration

- AEPS Contract (Aerojet Rocketdyne)
  - Hall Current Thruster
- In-House (GRC/JPL)
  - In-line Testing & Modeling
  - Contract Oversight
  - Independent Design Assessment

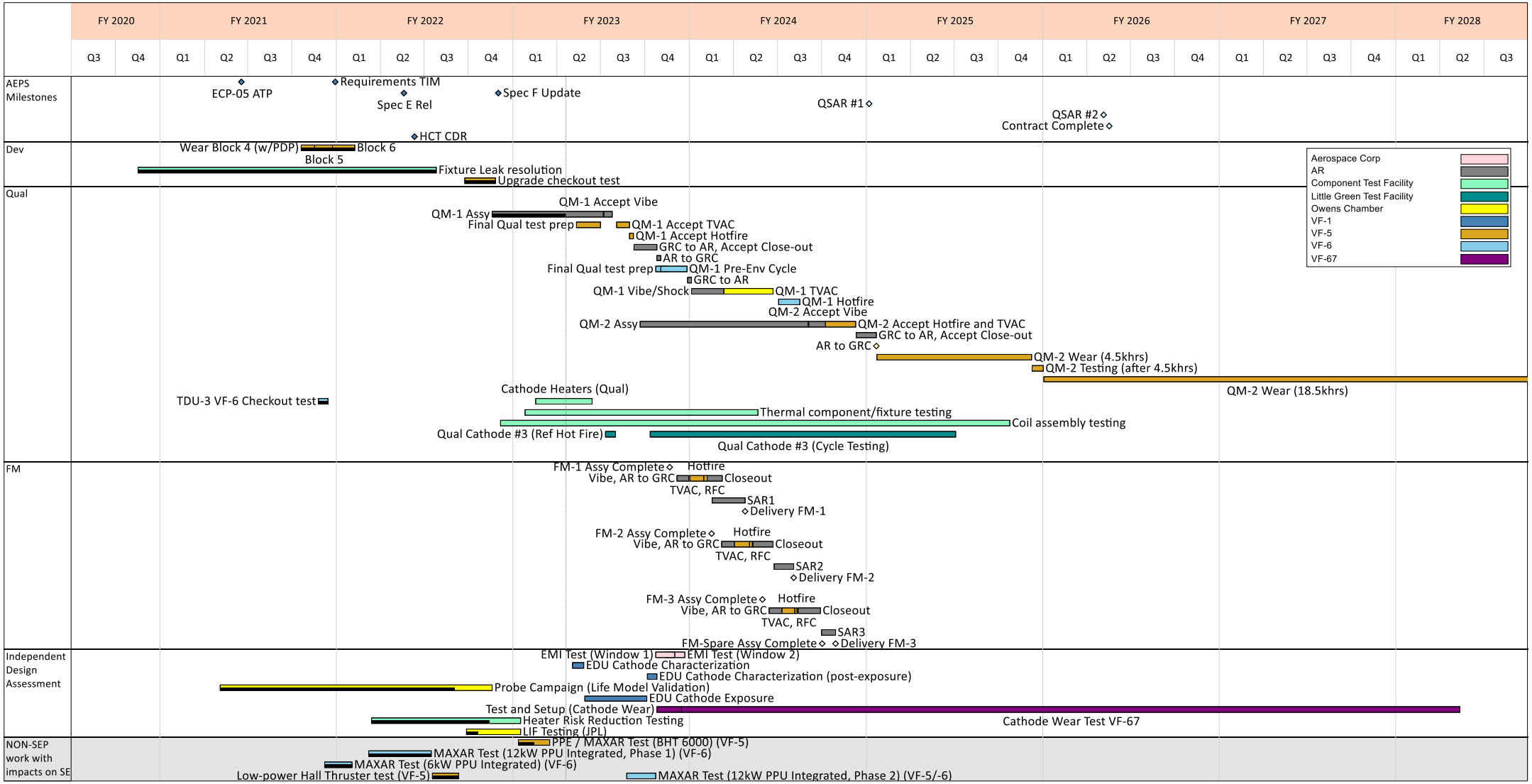
AEPS Key Milestones



CLIN 7 (Qualification Dev & Test) Major Milestones	ECP-07 Baseline	December Month End IMS	Schedule Margin (Working Days)
QM-1 Final Assy Complete	04/07/2023	02/28/2023	25
QM-2 Final Assy Complete	06/04/2024	01/11/2024	100
QSAR1	10/07/2024	10/07/2024	0
4500 Hour Wear Test Complete	11/03/2025	9/26/2025	0
QSAR2	02/04/2026	12/16/2025	26
CLIN 7 Complete	2/16/2026	2/16/2026	0
18500 Hour Wear Test Complete (SEP)	Q4 2028	Q4 2028	0

CLIN 8 (PPE Flight Thruster Build) Major Milestones	ECP-07 Baseline	December Month End IMS	Schedule Margin (Working Days)
FM-1 Thruster Assembly Complete	09/05/2023	05/15/2023	77
FM-1 Delivery	01/30/2024	01/30/2024	0
FM-2 Thruster Assembly Complete	12/06/2023	08/02/2023	86
FM-2 Delivery	04/29/2024	04/29/2024	0
FM-3 Thruster Assembly Complete	03/13/2024	10/19/2023	96
FM-3 Delivery	07/30/2024	07/30/2024	0

SEP – EP Thruster Integrated Schedule

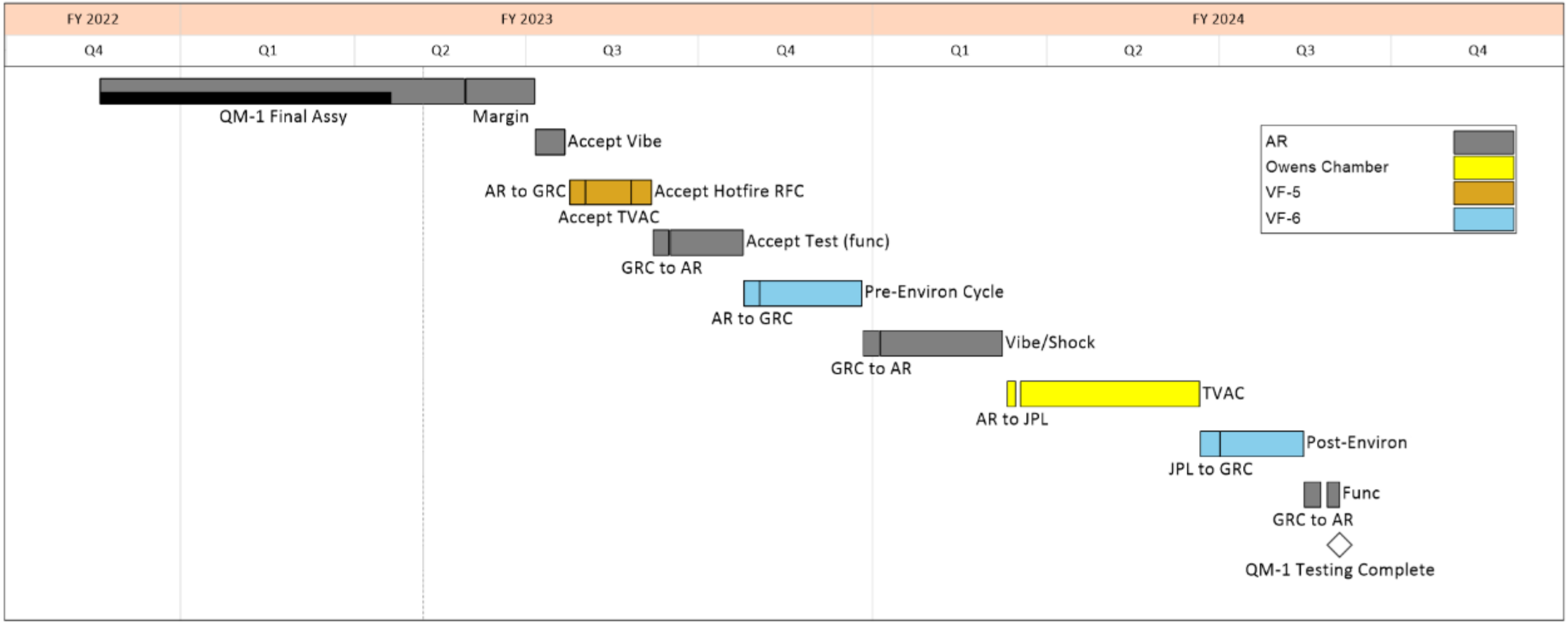


SEP Schedule 2023 01 19 v2 IMS incl testing.mpp

Snapshot Date: 1/19/2023

lifecycle7 F4 GW simple

SEP – QM1 Testing Schedule



SEP Schedule 2023 02 06 v3 IMS incl testing.mpp

Snapshot Date: 2/6/2023

QM1 testing f9